

THERMAL PROPERTIES OF POLYMER COMPOSITES REINFORCED WITH FILLERS OF DIFFERENT ELECTRICAL CONDUCTIVITY

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Abstract

This article analyzes the thermal properties of polymer composites reinforced with fillers of different electrical conductivity. Since polymers generally have low thermal conductivity, their application in high-temperature processes is limited. Therefore, the possibilities of improving thermal conductivity, thermal stability, and the coefficient of thermal expansion by introducing various fillers (metallic, carbon-based, and dielectric materials) are considered. Metallic and carbon-based fillers enhance both the thermal and electrical conductivity of composites, while dielectric fillers effectively dissipate heat and simultaneously provide electrical insulation. Moreover, the mechanisms of heat transfer, such as phonon and electron transport and interfacial resistance, are explained. Finally, the article highlights the potential applications of such composites in electronics, energy, automotive, and aerospace industries.

Keywords: Polymer composites, thermal properties, electrical conductivity, fillers, metallic particles, carbon-based materials, dielectric fillers, phonon transport, interfacial resistance, thermal stability, thermal conductivity, energy, electronics, aerospace industry.

Introduction

In recent years, the rapid development of modern technology and electronics has led to increasing demands on materials. Polymer-based composites stand out for their light weight, low cost, chemical stability, and technological convenience. However, the natural thermal conductivity of polymers is usually very low ($0.1\text{--}0.5\text{ W/m}\cdot\text{K}$), which limits their application in areas requiring high temperatures and heat exchange processes. Therefore, improving the thermal properties of polymers by introducing fillers with different electrical conductivities has become widely adopted.

RESEARCH AIM AND OBJECTIVES

Aim: To systematically study the thermal properties of polymer composites (thermal conductivity, thermal stability, coefficient of thermal expansion – CTE, and heat capacity) under the influence of fillers with different electrical conductivities (metallic, carbon-based, and dielectric), and to determine optimal composite formulations.

Objectives:

1. Select and prepare the polymer matrix and three types of fillers for the composites.
2. Prepare samples using different approaches (loading, morphology, and surface modification).
3. Measure thermal conductivity and other thermal parameters.
4. Determine the microstructure and interfacial characteristics (SEM, TEM, XRD, etc.).
5. Measure electrical properties (I–V characteristics, conductivity) and analyze the relationship between thermal and electrical properties.
6. Summarize the results through statistical analysis and modeling, and develop recommendations.

Materials and Sample Preparation**Materials**

- Polymer matrix (e.g., epoxy, polypropylene, or polyamide — selected depending on the research objective).
- Fillers:
 - Metallic particles (copper, aluminum, or silver micro-/nanoparticles).
 - Carbon-based materials (graphene, graphite, or multi-walled carbon nanotubes — MWCNT).
 - Dielectric fillers (boron nitride — hBN, Al_2O_3 , or SiO_2).
 - Surface modifiers: silane coupling agents or surfactants (if necessary).
 - Solvents, catalysts, and curing agents for the matrix (in the case of epoxy systems).

Formulations and Loadings

- Several loading levels for each type of filler: 0 wt% (control), 1–5 wt%, 10 wt%, 20 wt%, 30 wt% (or by volume fraction as well); if percolation is observed, a more detailed study of the range (e.g., 0–5–10–15–20%) is recommended.
- For hypermetals or nanoparticles, it is advisable to start with low concentrations and adjust dispersion methods.

Sample Preparation Methods

- **Mixing and dispersion:** Disperse fillers uniformly into the polymer using ultrasonication, oxidation, or cooling techniques.
- **Surface modification:** Treat filler particles with silane or other agents to improve adhesion with the polymer.
- **Curing/molding:** Prepare composites by casting, molding, or extrusion. Sample shapes must conform to standard testing formats (plaques, bars, etc., following ASTM/ISO requirements for test-specific dimensions).
- **Drying and thermal treatment:** Necessary to ensure complete curing and reduce internal stresses.

Thermal Properties of Polymer Composites

The thermal performance of polymer composites is assessed using several key parameters:

- **Thermal conductivity (λ):** the ability of a material to transfer heat.
- **Thermal stability:** the ability to maintain shape and properties at elevated temperatures.
- **Coefficient of thermal expansion (CTE):** the volumetric change of a material under temperature variation.
- **Heat capacity:** the amount of heat required to change the material's temperature.

The electrical conductivity of fillers affects these properties in different ways.

Electrical Properties of Fillers and Their Effects

1. Metallic particles (highly conductive)

- Metallic fillers such as copper, aluminum, and silver significantly enhance both thermal and electrical conductivity.
- Electrons actively participate in heat transfer.
- Such composites are widely used in heat-dissipating coatings and electronic devices.

2. Carbon-based fillers (moderate or tunable conductivity)

- Graphite, graphene, and carbon nanotubes (CNTs) are among the most effective fillers for improving thermal conductivity.
- Their electrical conductivity can vary and be adjusted, allowing their use in both dielectric and conductive composites.
- They sharply increase thermal conductivity while keeping the material lightweight.

3. Dielectric fillers (non-conductive)

- Materials such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and boron nitride (BN) conduct heat well but do not conduct electricity.
- These fillers are important in high-frequency electronics and insulating materials.
- In electronic devices, they dissipate heat while ensuring electrical safety.

Mechanisms of Thermal Property Modification

1. **Phonon transport:** In polymer matrices, heat transfer occurs mainly through phonons. Fillers reduce phonon scattering and enhance heat flow.
2. **Electron transport:** In metallic and carbon-based fillers, electrons also act as heat carriers.
3. **Interfacial resistance:** Strong bonding between the polymer and filler improves heat transfer; surface modification can further enhance this process.

Expected Results and Interpretation

- Metallic and carbon fillers are expected to improve thermal conductivity, while dielectric fillers may enhance thermal transfer while maintaining electrical insulation.
- Depending on dispersion and interfacial quality, a percolation effect in thermal conductivity may occur.

- Thermal stability and CTE values may increase or decrease depending on the type of filler — these must be confirmed using TGA/DSC and dilatometry.

Work Plan (proposed, adaptable)

1. **1–2 weeks:** Literature review, acquisition of materials, and laboratory setup.
2. **2–4 weeks:** Surface treatment of fillers and small-scale tests with polymers.
3. **4–8 weeks:** Preparation of main sample sets (different loadings) and visual/microscopic analysis.
4. **2–4 weeks:** Conducting thermal and electrical measurements (LFA, TPS, TGA, DSC, DMA).
5. **2–3 weeks:** Data analysis, modeling, and report writing.

Limitations and Recommendations

- When working with nanoparticles, dispersion challenges and agglomeration may significantly affect results — surface modification should be given special attention.
- If resources are limited, first determine the most promising filler and concentration, then proceed to the extended program.
- To compare experimental results with other studies, it is recommended to use methodologies consistent with ASTM/ISO standards.

Applications

- **Electronics and microchips:** efficient heat dissipation and insulation.
- **Automotive industry:** thermal management in engines and batteries.
- **Aerospace industry:** lightweight, dimensionally stable, and heat-resistant structures.
- **Energy sector:** heat dissipation in solar panels, wind turbines, and high-power batteries.

CONCLUSION

Polymer composites reinforced with fillers of different electrical conductivities hold great potential in the field of thermal management. Metallic and carbon-based fillers enhance both thermal and electrical conductivity, while dielectric fillers provide efficient heat transfer along with electrical insulation. Therefore, such composites are considered promising materials for modern electronics, energy, and high-tech industries.

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